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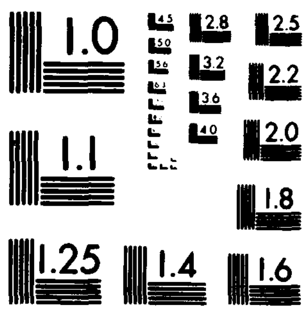

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This paper reports results from a study conducted by the Defense Mapping Agency (DMA) to determine the sensitivity of terrain profiling accuracy to input image quality. The study was accomplished by building a set of stereo test models over a test site; exercising those test models with current instruments; reducing the resultant profile data and comparing the results to existing ground control for the test site. The test models were produced from single model by repeated steps of photographic enlargement, reduction

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PROFILING SENSITIVITY TO IMAGE QUALITY

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BIOGRAPHICAL SKETCH

Mr Moellman is employed as a Physical Scientist with the Defense Mapping Agency Aerospace Center, St Louis, Missouri, in the Acquisition Systems Development Division of the Systems and Techniques Directorate. He began his career with DMAAC in 1963 and has remained there with the exception of 1976-1978 when he was assigned to Headquarters Defense Mapping Agency, Washington, DC. In his present capacity he is closely associated with digital sensor technology and digital data exploitation methodologies. Mr Moellman's educational background consists of BS and MS degrees from the University of Illinois. His professional society affiliation is the American Society of Photogrammetry.

ABSTRACT

This paper reports results from a study conducted by the Defense Mapping Agency (DMA) to determine the sensitivity of terrain profiling accuracy to input image quality. The study was accomplished by building a set of stereo test models over a test site; exercising those test models with current instruments; reducing the resultant profile data and comparing the results to existing ground control for the test site. The test models were produced from a single model by repeated steps of photographic enlargement, reduction and resolution degradation. The resultant 25 test models represented all combinations of five specific image scales and resolutions. The instruments were operated in both manual and automatic correlation modes. As a consequence the results portray the interdependence of profile accuracy with both scale and resolution as well as the effects of both manual and automatic profiling. The results also provide insight into the behavior of automatic correlation when approaching and exceeding the instrument's theoretical minimum resolution threshold.

INTRODUCTION

BACKGROUND. Almost every DMA product which requires photographic source for its production contains topographic relief portrayed in the form of either a digital terrain elevation matrix or a contour plot. Today, regardless of its portrayal, topographic relief is derived from Digital Terrain Elevation Data (DTED) which is collected by analytical stereoplotters in the form of terrain profiles and stored in data bases. This raw DTED is then computer processed and transformed into the final form and format required.

When considering the production capability of a photographic source, its image quality characteristics and scale play a major role in determining its utility. Upon investigation, it became apparent that there was little quantitative experience regarding the independent or combined effects of quality and scale upon DTED accuracies. Over the past several years topographic relief compilation methods have evolved from directly collecting contours to collecting DTED in the form of terrain profiles. Hence, the previous experience base needed at least a re-examination.

To be meaningful such a re-examination should be geared to proposed new sensors and collection scenarios. A couple worthy of note are the MAPSAT (1) and Large Format Camera (2) sensors proposed for the Space Shuttle. These represent satellite-borne collection scenarios which lead to small scale and ground resolution of 45 feet to 100 feet. Several investigations (3, 4, 5) have discussed the relationship between image quality and metric capability in the context of utilizing space-borne sensors with their resulting small scale and low resolution characteristics. However, these primarily dealt with pointing accuracies achievable on discrete targets with only some theoretical considerations made concerning topographic compilation accuracies. Moreover, when considering automatic correlation techniques for terrain profile collection, theory (6) has it that the optimum frequency for precision correlation, due to photo grain noise and spot size used in automatic correlators, is between 5 line pairs/millimeter (lp/mm) and 10 lp/mm. If that is true, then automatic correlation techniques applied to space-borne sensors may suffer because at those small scales it appears that, in comparison to normal aerial photography, there will be little photographic texture in the imagery for automatic correlators if they respond only to low frequency data.

<u>OBJECTIVES.</u> It was therefore the objective of this study to fill some of the information gaps and to answer some of the questions just posed. More specifically, the primary objective was to determine the effects of image quality upon DTED collection accuracy, in both an automatic and manual mode. A secondary objective to be addressed was to assess the additional effects of image scale upon accuracy.

It is felt that satisfying these objectives would provide insight into the utility of shuttle-borne sensors, similar to those cited earlier, for DTED collection. The experimental design provides an opportunity to investigate the interrelationships between image quality and scale in typical space-borne collection scenarios. It also enables examination of automatic correlation behavior when approaching and exceeding the instrument theoretical minimum frequency (resolution) threshold and to benchmark automatic correlatioin against manual correlation over a variety of conditions.

<u>SCOPE</u>. The following constraints were imposed on this study in order to shorten the elapsed time for the experiment and to minimize the expenditure of manpower and equipment resources:

- The source imagery from which all test samples were derived was a single, high-resolution stereomodel.
- Six profiles were selected to represent the collection area.
- An analytical stereoplotter incorporating automatic correlation of conjugate images was used for automatic profile collection.
- An analytical stereoplotter with manual operator control was used for manual profile collection.

<u>SCENARIO</u>. The basic scenario was to select a high-resolution stereomodel over a well-controlled area, and systematically degrade the image resolution in order to develop the test imagery. These stereomodels were then compiled sequentially, beginning with the lowest resolution model and ending with the highest resolution model. The compilations, performed in both the manual and automatic stereo compilation modes, constituted the

experimental portion of this study. A single instrument operator performed the manual compilation portion of the experiment for all test samples.

The remainder of the scenario was to reduce and analyze the experimentally collected data. This involved comparing the various compilation portrayals of the terrain to known ground control points. From the analysis of this data, the sensitivity of the DTED accuracy to image quality was determined.

The scenario just described has been captured in Figure 1, which depicts the steps in chronological order. In order to support the actual experiments, two sets of input data were developed. These data consisted of a set of test photos and a network of ground control. The ground control provided reference points required to orient the stereomodels comprised of the stereopair test photos. In the next step, the instrument experiment, stereomodels were set up on the photogrammetric plotters and profiles of elevation data were extracted. These profiles were compared to ground truth in order to determine the accuracy achievable with each level of resolution and photo scale. In the final step, the experimental results were used to derive minimum resolution thresholds for photogrammetric compilation.

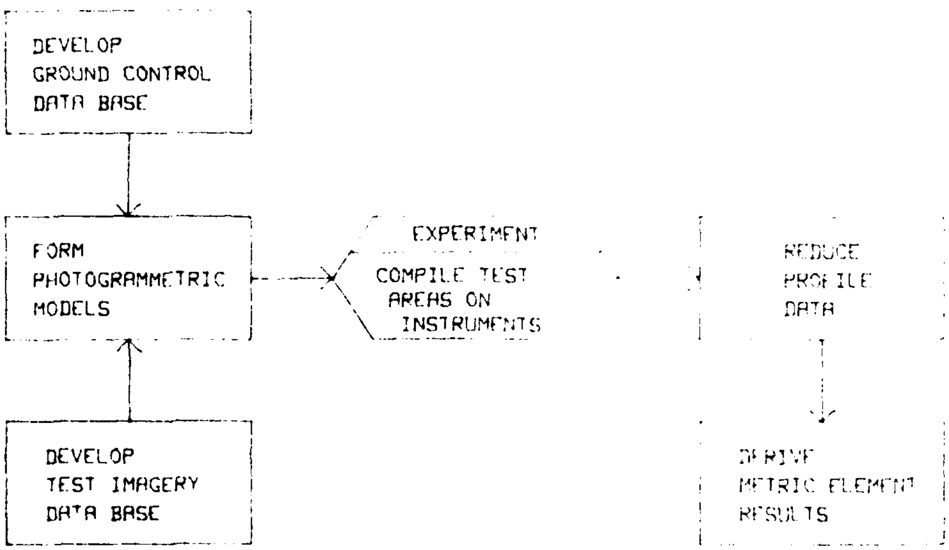

FIGURE 1: MAJOR STEPS

METHODOLOGY

INPUT DATA BASES. As shown in Figure 1, two sets of data were input to the actual instrument experiment. One was the test imagery and the other was ground control for the test site. Both inputs simultaneously influenced the test area selection and, ultimately, the test site selection. Collectively, the criteria established by the inputs dictated that all of the following must be true of the test area: 1) high resolution and small scale coverage must exist, 2) the terrain must exhibit moderate relief, and 3) ample first order ground control must be available. In order to provide input for the instrument experiment, two input data bases were established. Details of their derivation and characteristics are provided in the following paragraphs.

TEST IMAGERY: A search for a test area was initiated in which several candidate areas were screened against the criteria cited above. The candidates were subsequently reduced to those areas where a sufficient amount of cultural detail was present in order to quantitatively assess image quality in terms of ground resolved distance (GRD). Precise image quality data was necessary to enable quality control of the photo reproduction through several resolution degradation steps. The Fort Huachuca area was eventually selected because it was the only test site that met all criteria. The imagery selected was from a KA-54A panoramic camera. The test area was only 3° from scan center of the stereopair. The scale was 1:110,000 and the file copy film resolution was evaluated at 132 lp/mm or 2.6 feet GRD. The stereopair has a B/H ratio of 0.35.

Figure 2 shows the location of the test site in the Fort Huachuca vicinity. The actual site was selected because it contained a minimum of built-up (cultural) area and a variety of terrain relief. The area outlined in Figure 2 measured approximately 2.25" x 2.25" on the imagery. The test site area was constrained to that size to accommodate a 4X enlargement of it on the 9.5" wide stereoplotter carriages.

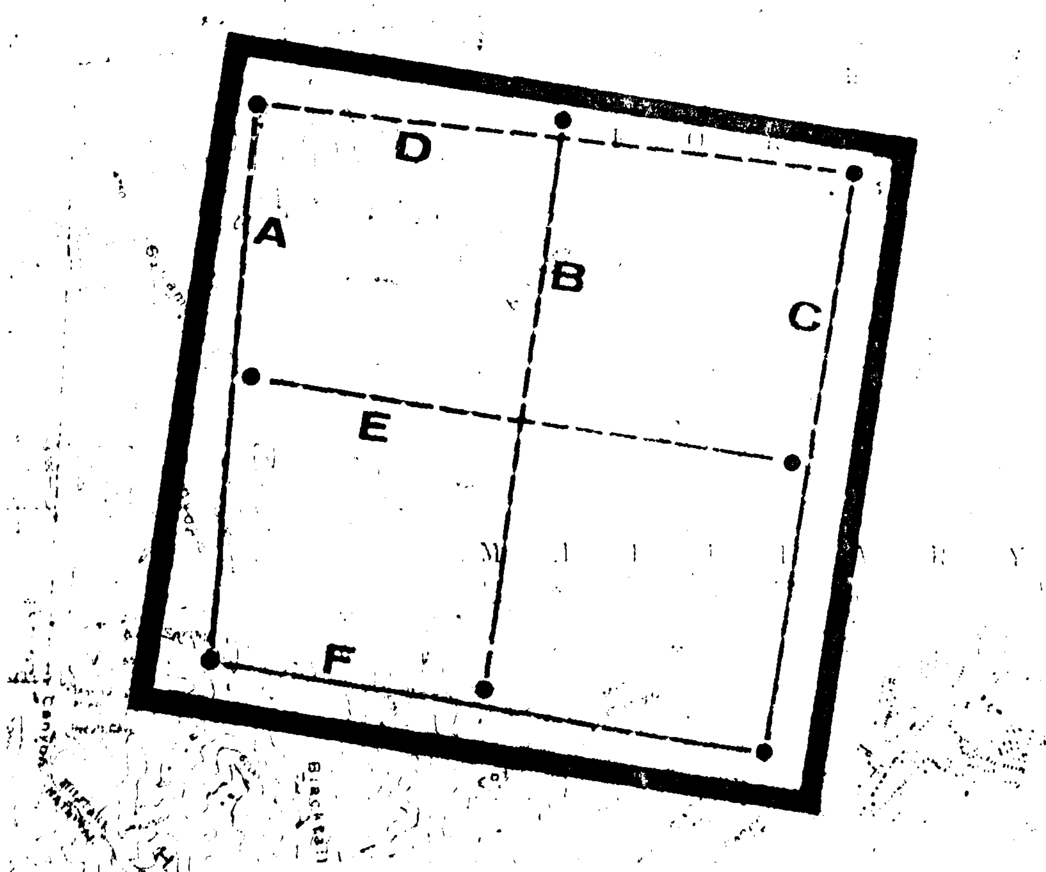

FIGURE 2: FORT HUACHUCA TEST AREA

After the test site and file imagery source were selected, the test imagery was produced. The intent was to produce a matrix of 25 stereomodel test samples to cover a broad range of resolution and scale as shown in Table 1.

	(GRD)					
Scale	5'	10'	25'	50'	100'	Scale Change
1:27.5K	17	8	3	2	1	4:1
1:55K	34	17	7	3	2	2:1
1:110K	72	34	14	7	3	1:1
1:275K	172*	86*	34	17	9	1:2.5
1:550K	343*	172*	69	34	14	1:5

Table 1 Test Sample Matrix

Each matrix entry in the table represents the stereomodel film resolution, in lp/mm, required by its scale to achieve its respective GRD. The last column in Table 1 represents the ratio between test sample scales and the file copy imagery from which each test sample was photographically produced. The laboratory processes comprised reduction or enlargement and the required resolution degradation. The four samples in the table, denoted with asterisks, could not be produced with the required resolution and were not included in the final test samples.

Extreme laboratory quality assurance measures were taken in producing the test samples. In samples with sufficient scale enlargement to preclude the cultural detail by which the resolution could be measured, a resolution target was spliced into the file copy, which appeared on all subsequent reproductions. A density wedge was also spliced into the file copy to insure that all copies (test samples), regardless of their scale or resolution, would have the same contrast.

GROUND CONTROL: Ground control points for the test area were developed from three U.S. Geological Survey (USGS) 1:24,000 scale maps; O'Donnel Canyon, Arizona; Pyeatt Ranch, Arizona; and Fort Huachuca, Arizona. All horizontal control was on the North American Datum (Clark 1866) and elevations referenced to mean sea level. After points were scaled from the source maps, their coordinates were transformed to World Geodetic System 72 (WGS 72) and mean sea level. All ground control points selected were identifiable, both on the map and the photos. The maps met National Map Accuracy Standards with a 25-foot contour interval and a spot elevation accuracy of ± 12 feet at 90 percent linear error (LE).

A grid of 30 well-distributed control points was selcted for stereomodel orientation. These control points were distributed over the length of the file copy film, thus extending far beyond the limits of the test site. This extension of control was required in order to provide adequate geometry for subsequent model orientation and setup on the stereoplotter.

A set of six terrain collection profiles spanning the test site were laid out. As shown in Figure 2, three profiles, labeled A, B, and C were oriented nominally North-South, and three, labeled D, E, and F, East-West. End points for each profile were identified on the imagery and transferred to the map source. Profile lines were then drawn connecting the end points. Ground "truth" points were plotted at each intersection of the profile line and the map contour line. Elevations for these points were determined by the contour elevations. Consequently, as shown in Table 2, the number of points along a given profile is directly proportional to the amount of terrain relief along that profile.

Profile	Number of Points
A	31
B	41
C	37
D	40
E	45
F	139
TOTAL	341

Table 2 Distribution of Truth Points by Profile

INSTRUMENT PROCEDURE. In this data collection process, three different compilation methods were employed: manual profile compilation on the AS-11BX (operated as a manual instrument with its automatic correlation circuitry locked out), automatic profile compilation on the AS-11BX, and automatic profile compilation on the UNAMACE. The former two methods were performed at DMAAC, and the latter at DMAHTC. In all cases, the same imagery test samples were used.

The instrument procedure utilized was similar to that used in DTED production, but with a few shortcuts incorporated for the manual compilation method to minimize resource expenditure. The instrument procedure comprises two phases: model setup and compilation. Compilation involves the actual extraction of DTED from a stereomodel, and model setup encompasses all activities involved in the preparation of the stereomodel for compilation. In order to avoid the introduction of operator biases in the results of the manual compilation method, two instrument operators were used; one set up the model and the other compiled the DTED profiles. Detailed descriptions of the model setup and compilation processes are described chronologically in the following paragraphs.

MODEL SETUP: This process comprised three functional operations called interior orientation, relative orientation, and absolute orientation. In this context, interior orientation has a dual meaning. First, in the classical sense, it involves capturing the sensor internal geometry at the istant of imaging. Second, it involves establishing the correspondence between the imagery coordinate system and that of the stereoplotter. Relative orientation involves the determination of the relative position and orientation in space of one constituent of a stereopair with respect to its mate, thus forming a stereomodel. Absolute orientation is an operation in which the stereomodel is scaled and positioned in a model coordinate system that is tied to an earth fixed reference system which, for this study, is WGS 72 and mean sea level.

While the model setup procedures for both instruments are functionally the same, there are, however, slight differences in implementation. Because of the similarity, only the AS-11BX instrument procedure will be addressed in the ensuing paragraphs.

Interior Orientation. All imagery comprising the test samples were produced from the file copy film on which was superimposed a reseau of intersecting line segments spaced at a three centimeter intervals. A 3 x 3 array of reseau marks fell within the area of the test site in the imagery. The outermost four reseau marks were used in the interior orientation. In some samples in which the resolution was severely degraded, the reseau marks could not be identified. In those instances, a stereotransfer procedure was employed to identify and physically mark their locations.

This was accomplished with a point transfer device while viewing stereoscopically one high resolution sample and one degraded resolution sample. Once placed on the AS-11BX along with the setup parameters, an instrument interior orientation was performed on the highest resolution stereomodel at each model scale. Thus, only five separate interior orientations were accomplished to accommodate all test samples. Separate interior orientations were not required for manual and automatic compilation.

Relative Orientation. An automated, on-line two projector method was used to perform a relative orientation for all sample stereomodels on the AS-11BX. The 2:1 and 4:1 scale stereomodels required additional treatment with an automated, on-line one projector method. Once again, one relative orientation solution was performed for each scale stereomodel. The same solution was subsequently used for all stereomodels of that particular scale.

Absolute Orientation. The actual stereomodel compilations were performed in a Local Space Rectangular (LSR) coordinate system. Ground control point coordinates were transformed to the LSR system. The LSR system was chosen so that the stereomodel Y-axes were parallel in order to maximize automatic AS-11BX collection. The LSR control point locations and corresponding model readings from the relative orientations were processed in an off-line computer program to derive preliminary absolute orientation elements and transformed model coordinates. Then the transformed model coordinates and their corresponding model readings were input to a least squares adjustment program. The program accomplished a linear, nonconformal fit between the two coordinate systems in each of the X, Y, and Z axis. This last step of the absolute orientation process, a standard production procedure, is used to minimize the effects of previously unmodeled sensor and film processing errors.

COMPILATION: The compilation embraced the extraction of DTED from each sample stereomodel in order to costruct its six representative profiles. The AS-11BX has a fixed collection interval built into it. Raw data point outputs are collected in intervals of .32mm in the model x-direction and .30mm in the model y. To insure compatible data collection, the same collection interval was maintained for both automatic and manual compilation processes. Any difference in accuracy between the two modes can only be accounted for by the difference between automatic correlation versus manual tracking capability, and not by a difference in the density of output data points. The manual and automatic compilation processes are sufficiently different to justify separate treatment. Each, then, will be addressed in the following paragraphs.

Manual. Besides the use of two separate instrument operators, an additional precaution was taken to avoid contaminating the results. Data collection began with the stereomodel having the smallest scale and the poorest resolution (i.e. 1:5 and 100 feet GRD) and continued through all stereomodels in each scale range with the poorest resolution model being compiled first. Then the group of models with the next largest scale was compiled until all stereomodels had been completed. This scenario was instituted to minimize carryover, from a better resolution model to a poorer one, due to the operator gaining familiarity with the test site. As will be seen in the results section, several of the small-scale poor-resolution models could not be compiled. This circumstance arose for both manual and automatic compilation modes.

To begin the manual collection for a stereomodel, the initial and terminal points for each profile were occupied and their coordinates used to compute a profiling direction. The actual data collection extended beyond

the end points of each profile and encompassed a number of profiles on either side of the desired profile. Such "over-sampling" was necessary to insure an adequate density of interpolation points for comparison to ground truth profiles. Data was collected for each stereomodel in the sequence described above. All manual profile point data was collected by the operator, through the interface with the instrument, by maintaining proper stereo fusion of conjugate imagery as the instrument automatically drove along a profile at a speed controlled by the operator.

Automatic. Automatic collection was performed in a similar manner to the manual collection with one exception. As the scene was scanned, the instrument digitally sampled pixel densities simultaneously from both photos of the stereomodel, and compared them to achieve fusion of conjugate images automatically. The automatic operation takes place so rapidly that profiles of the entire test site area were collected, rather than selected subsets.

DATA PROCESSING. Once the data was collected, there remained two processing steps before tangible results could be achieved: first, final stereomodel profiles had to be interpolated from the raw DTED and, second, the profiles had to be compared to ground truth. Descriptions of those two steps follow.

PROFILE DETERMINATION: An X and Y coordinate location is associated with each elevation point. The raw DTED is comprised of a matrix array of these three-tuples. The ground truth profiles represent elevation values for specified X and Y locations. The object was to interpolate elevation values for the representative profiles at corresponding X and Y locations from the matrix of raw DTED. The calculation of each final elevation was interpolated from four surrounding raw data elevations using a bilinear interpolation algorithm. The contribution of each surrounding point was weighted inversely proportional to its distance from the desired point (position error). In both the manual and automatic collection modes, sufficient data was collected to support this interpolation procedure.

PROFILE COMPARISON: Once obtained, each resultant profile was compared to its ground truth. For each profile, that scenario was a point by point computation of algebraic deltas. Each delta, Δij, represented a ground truth elevation, (Z_{ij}), minus its collected/derived elevation value, $(Z'ij)$, as shown below:

$$\Delta ij = Z_{ij} - Z'_{ij}$$

where subscript i denotes the point and subscript j denotes the profile.

Next, elevation standard deviations of each profile were computed by:

$$\sigma j = \left[(\Delta ij - \Delta j)^2/(n - 1) \right]^{1/2}$$

where Δj is the mean delta value for the jth profile. Similarly, standard deviations for each test sample were computed taking into account the points in all six profiles.

RESULTS

The results of the experimental process, after the appropriate data processing was completed, are summarized in Tables 3 and 4. The matrix format of these tables duplicates that of Table 1 which describes the test sample characteristics. Each entry represents the compilation elevation accuracy, in feet, raised to the 90 percent confidence level. It

should be noted that these tables have missing entries in addition to those for which no test samples could be photographically produced. Those omissions, concentrated in the upper right quandrant of the tables, arose when the combined effects of degraded resolution and large scale would not permit compilation. In those instances, the imagery lacked sufficient detail (texture), precluding human stereo fusion or electronic correlation of the images. Referring to Table 1, it is apparent that those occurrences were stereomodels whose photos contained the lowest lp/mm resolutions.

Scale	Resolution (GRD)				
	5'	10'	25'	50'	100'
4:1	29.9	30.4	29.2	-	-
2:1	28.5	29.4	32.4	31.9	-
1:1	25.0	25.5	24.8	30.5	50.8
1:2.5	-	-	36.8	46.8	72.5
1:.5	-	-	50.0	48.2	68.5

Table 3 Summary of Manual Profiling Accuracy (in feet)

Scale	Resolution (GRD)				
	5'	10'	25'	50'	100'
4:1	28.5	25.4	27.6	-	-
2.1	25.4	26.8	20.1	45.1	-
1:1	33.0	47.7	48.5	75.0	133.2
1:2.5	-	-	72.5	110.8	277.8
1:.5	-	-	120.4	167.6	190.8

Table 4 Summary of Automatic Compilation Accuracy (in feet)

From the data provided in Tables 3 and 4 it can be seen that compilation accuracy is affected by both photo resolution and scale. To summarize, the results are:

• Photo Resolution (lp/mm). Resolution affects the ability of an operator to fuse stereo images and electronic/video equipment to correlate stereo images. The data indicates that below a threshold level, fusion/ electronic correlation is not possible. The absolute lower limit appears to be about 3 lp/mm but the data indicates the (vertical) accuracy begins to be affected at about 15 lp/mm. The threshold for human fusion is somewhat lower than for electronic correlation.

• Photo Scale. Scale affects the precision and accuracy of vertical measurements. At smaller scales, the least count (minimum elevation increment) of the instrument becomes a contributing factor in measurement precision. In automatic compilation systems, the area over which automatic correlation takes place increases with decreasing scale. Since elevation measurements are based on the "average" of the area correlated, the accuracy is educed with decreasing scale. In manual compilation, the tracking toler .e required to achieve a specified accuracy decreases with de- rea .ng scale, thus also lowering compilation accuracy. These characteristics are dramatically portrayed in the 1:2.5 and 1:5 scale reduction data sets. Compilation accuracy, however, does not improve at scale enlargements because the resolution approaches the 10-15 lp/mm level where accuracy is affected by the resolution limit discussed above.

In general, it can be said that resolution affects stereo compilation below a threshold that falls somewhere between 15 and 3 lp/mm. Above that threshold, manual and automatic compilation capability is not affected. Above the resolution threshold, however, compilation accuracy is affected by image acquisition conditions, one of which is photo scale. With everything else equal, scale, by itself, has the effect of reducing accuracy as the scale gets smaller. The absolute effect of scale can be determined only in context with the other acquisition parameters.

If one compares same scale entries in Table 4, it can be seen that there are some indications that the automatic correlator responds favorably to image frequencies above the 10 lp/mm theoretical cutoff. With the limited data samples one could only speculate as to the cause.

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